



Closing the Loop for Aluminium Cans

Life Cycle Assessment of progression in Cradle-to-Cradle certification levels

Niero, Monia; Negrelli, Anthony Johannes; Hoffmeyer, Simon Boas; Olsen, Stig Irving; Birkved, Morten

Published in:
Journal of Cleaner Production

Link to article, DOI:
[10.1016/j.jclepro.2016.02.122](https://doi.org/10.1016/j.jclepro.2016.02.122)

Publication date:
2016

Document Version
Peer reviewed version

[Link back to DTU Orbit](#)

Citation (APA):
Niero, M., Negrelli, A. J., Hoffmeyer, S. B., Olsen, S. I., & Birkved, M. (2016). Closing the Loop for Aluminium Cans: Life Cycle Assessment of progression in Cradle-to-Cradle certification levels. *Journal of Cleaner Production*, 126, 352-362. <https://doi.org/10.1016/j.jclepro.2016.02.122>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Closing the loop for aluminium cans: Life Cycle Assessment of progression in Cradle-to-Cradle certification levels

Monia Niero ^{a,§}, Anthony Johannes Negrelli^{a,b1}, Simon Boas Hoffmeyer^b, Stig Irving Olsen^a, Morten Birkved^a

^a Division for Quantitative Sustainability Assessment (QSA), Department of Management Engineering, Technical University of Denmark, Produktionstorvet 424 DK-2800 Kgs. Lyngby.

^b Group Corporate Affairs, Carlsberg Breweries A/S, Ny Carlsberg Vej 100 DK-1799 Copenhagen V

¹ Current address: Siemens Wind Power A/S WP OF CNS TS Fiskergade 1-9 DK-7100 Vejle

[§] Corresponding author email: monni@dtu.dk; telephone: +45 45251640

E-mail addresses: Anthony J. Negrelli (anthony.negrelli@siemens.com); Simon B. Hoffmeyer (simon.boas@carlsberg.com); Stig I. Olsen (siol@dtu.dk); Morten Birkved (birk@dtu.dk)

Abstract

Despite their different scopes, both the Life Cycle Assessment (LCA) methodology and the Cradle to Cradle (C2C) CertifiedTM Product Standard can support companies in the implementation of circular economy strategies. Considering the case of aluminium cans, the objectives of this paper are twofold: (i) to compare the environmental impact associated with different levels of two C2C certification requirements by using LCA; and (ii) to identify the main challenges and drawbacks in the combined use of LCA and C2C for packaging within the circular economy framework.

Twenty different scenarios were developed and compared, according to three C2C certification levels, in terms of % renewable energy and % recycled content. The results show that increasing the recycled content provides more improvements to environmental impacts than increasing renewable energy usage.

Furthermore, receiving a higher certification level does not necessarily mean environmental burden reduction in LCA sense.

From a methodological point of view, the main challenge for LCA is to address the continuous loop of materials and account for the benefits from recycling in a consistent way. Meanwhile for C2C the challenge is to guarantee a proper translation of the C2C principles into the C2C certification program, avoiding burden shifting and to find a balance between the different certification requirements.

Keywords: circular economy, LCA, cradle to cradle, packaging, scenario analysis, recycling

Abbreviations

APEAL = Association of European Producers of Steel for Packaging

B = Bronze

BCME = Beverage Can Makers Europe

C2C = Cradle to Cradle®

C2C certification program = Cradle to Cradle Certified™ Product Standard

CCC = Carlsberg Circular Community

CED = Cumulative Energy Demand

EAA = European Aluminium Association

EoL = End-of-Life

EPD = Environmental Product Declaration

EPEA = Environmental Protection Encouragement Agency

FU = Functional Unit

G = Gold

GHG = greenhouse gases

GWP = Global Warming Potential

IEA = International Energy Agency

ILCD = International. Reference Life Cycle Data System

LCA = Life Cycle Assessment

LCI = Life Cycle Inventory

LCIA = Life Cycle Impact Assessment

MH = Material Health

MR = Material Reutilization

MRS = Material Reutilization Score

NRE = Non-Renewable Energy

PEF = Product Environmental Footprint

RC = Recycled Content

RE = Renewable Energy

RE&CM = Renewable Energy and Carbon Management

RR = Recycling Rate

S = Silver

S1= sensitivity analysis n. 1

S2 = sensitivity analysis n.2

S3 = sensitivity analysis n.3

S4 = sensitivity analysis n.4

S5 = sensitivity analysis n.5

SF = Social Fairness

UBC = Used Beverage Cans

WS = Water Stewardship

1. Introduction

Continuing population and consumption growth impose substantial challenges to the current consumption and production patterns (Godfray et al., 2010). Management of resources is one of the key aspects in pursuing a sustainable growth since continued exploitation of resources may lead to their depletion, i.e. loss of geological or natural reserves, and/or their scarcity, i.e. reduced economic availability of a resource (Klinglmair et al., 2013). However, most industrial sectors are nowadays still organized according to a linear economy, where resources are extracted and transformed to manufacture goods that are used by consumers and finally disposed. An alternative to this “take – make - waste” system is provided by the circular economy model, “an industrial system that is restorative or regenerative by intention and design”(EMF, 2013), which focuses on the most efficient and effective way to close product loops.

In the context of the circular economy, the Cradle to Cradle® vision (hereafter C2C) is gaining more and more visibility. C2C is a design framework oriented towards product quality and innovation, which aims to increase the positive environmental footprint of products by designing “eco-effective” solutions, i.e. maximizing the benefit to ecological and economical systems. C2C is based on three key principles for achieving eco-effectiveness: “waste equal food”, “use current solar income” and “celebrate diversity” (McDonough and Braungart, 2002). C2C defines a framework for designing products and industrial processes that turn materials into nutrients by enabling their perpetual flow within one of two distinct metabolisms: the biological metabolism and the technical metabolism (Braungart et al., 2007).

In addition to the design framework, a certification program known as the Cradle to Cradle Certified™ Product Standard (hereafter C2C certification program) was conceived to allow companies to visualize and market their progress in C2C compliance (Cradle to Cradle Products Innovation Institute, 2013). The certification program has a series of requirements in five quality criteria: material health (MH), material reutilization (MR), renewable energy and carbon management (RE&CM), water stewardship (WS) and social fairness (SF), with each criteria scored on five levels: basic, bronze, silver, gold, and platinum. The final certification of the product is equal to the minimum level of achievement on the scorecard (Cradle to Cradle Products Innovation Institute, 2013). Only platinum certified products are fully C2C compliant, but the different certification levels are meant to reward the effort of companies in the continuous improvement of their performance along the path towards eco-effectiveness.

The C2C design framework inspired the creation of the Carlsberg Circular Community (CCC), a cooperation platform launched in January 2014 featuring Carlsberg Group, the fourth largest brewing company in the world, and a selection of global partners aiming to rethink the design and production of traditional packaging material. The objectives of the CCC are twofold: (i) to analyse Carlsberg’s packaging portfolio from a C2C perspective, and develop products and materials that are optimised for re-entry as valuable resources into the biological or technical cycles, and (ii) to support the circular economy by improving quality and purity of packaging, with the ultimate aim to eliminate the concept of waste (Carlsberg Group, 2015).

Different types of packaging are considered in the C2C analysis within the CCC. Three primary packaging solutions are currently being evaluated from a C2C perspective, including the aluminum can. In January 2015, Carlsberg UK received bronze C2C certification for their Carlsberg and Somersby cans (size 44, 50 and 56.8 cl cans), as a result of the assessment performed by the Environmental Protection Encouragement Agency (EPEA) in collaboration with Carlsberg's aluminium can supplier Rexam (Carlsberg Group, 2015). In recent years extensive work has been performed by the aluminium beverage can industry, as well as by beverage companies, to measure the eco-efficiency of their products, by assessing their environmental performance using Life Cycle Assessment (LCA), (e.g. EAA, 2013; PE Americas, 2010; Stichling and Nguyen-Ngoc, 2009). These studies identify the energy consumption during primary aluminium manufacturing as the main hotspot in terms of environmental burdens. Therefore the use of secondary aluminium has been eagerly promoted in order to reduce the emissions of greenhouse gases (GHG) and reduce the reliance on primary aluminium (Sevigné-Itoiz et al., 2014). The influence of the type of energy used and the supply of either primary or secondary material is quantified in the C2C certification program through two distinct criteria: RE&CM, and MR, respectively, which are directly quantifiable in LCA terms, as detailed in Negrelli (2015). Furthermore, the collection and recycling rate of aluminium cans was identified as a key driver for the environmental impact in LCAs (Gatti et al., 2008; Stichling and Nguyen-Ngoc, 2009).

Both the eco-efficiency, e.g. LCA, and C2C concepts can support companies in the implementation of circular economy strategies, even though the two approaches have different scopes. Eco-efficiency aims to reduce the negative environmental footprint of human activities, while C2C, based on the eco-effectiveness concept, attempts to increase the positive footprint. What the eco-efficiency concept can learn from C2C (as presented by e.g. Bjørn and Hauschild (2013)) and other nature-inspired design approaches (de Pauw et al., 2014), as well as the usability of LCA in a C2C process (Bor et al., 2011) have already been assessed and presented. One of the outcomes of such analyses is that C2C products will not necessarily perform well in an LCA. Despite this C2C/LCA misalignment LCA remains the preferred tool to quantify the environmental improvements of products before and after the C2C certification (Llorach-Massana et al., 2015; Trucost, 2014). LCA is widely used as a decision support tool in the packaging industry, despite the influence of subjective choices on the outcomes of results, both at methodological (e.g. end-of-life (EoL) modelling (Toniolo et al., 2013)) and operative (e.g. software selection (Speck et al., 2015a)) levels. However, only one of these comparative studies, i.e. Speck et al. (2015a), included aluminium beverage cans in their scope. Furthermore, to our knowledge the changes in environmental impacts resulting from a shift between C2C certification levels have never been quantitatively assessed in LCA terms. Therefore, referring to the case of Carlsberg's aluminium cans, the objectives of the study are:

- i. to compare the environmental impact associated with different levels of two C2C certification requirements by using LCA;

- ii. to identify the main challenges and drawbacks in the combined use of LCA and C2C for packaging in the circular economy framework.

Hence, the comparison among the different C2C certification scenarios will identify which actions should be prioritized by the CCC in their progression in certification levels, e.g. from bronze to silver to gold. The discussion on the methodological constraints of a combined use of the two approaches will provide suggestions on how mismatches between the two approaches can be overcome and how synergies can be exploited.

2. Materials and methods

In this section, we present the details of the LCA methodology applied to the aluminium can case study (section 2.1), as well as how the selected C2C certification requirements have been modelled in the LCA (section 2.2).

2.1 Life Cycle Assessment

Based on the ISO 14040-44 standards (ISO, 2006a, 2006b) an LCA was performed according to four steps: (1) goal and scope definition, (2) Life Cycle Inventory (LCI), (3) Life Cycle Impact Assessment (LCIA) and (4) life cycle interpretation.

The packaging sector has to a large extent been using streamlined LCA tools combining ease of use and provision of reliable results in the design and development of sustainable packaging (Vergheze et al., 2010). Recent scientific publications target value choices of the LCA product system modelling approaches as implemented in product system modelling software and how these choices may influence the results of an LCA study (Speck et al., 2015b), particularly in the packaging sector (Speck et al., 2015a). In order to address these potential variances, we performed the LCA presented in this paper, using different software, i.e. the InstantLCA PackagingTM powered by RDC Environment (<http://www.rdcenvironment.be>) as a reference; and the most widely used LCA softwares, i.e. Gabi v.6.4 (<http://www.gabi-software.com>), and Simapro v.8.0.4.30 (<http://www.pre-sustainability.com/simapro>).

We modeled 20 different scenarios (see Table 1) complying to different degrees with two of the C2C certification requirements, namely RE and MR. A scenario analysis compared the environmental impacts associated with three different levels of C2C certification, i.e. bronze (B), silver (S) and gold (G). The basic certification level was disregarded because this level is an entry level to the C2C assessment and only requires an initial (C2C) screening of a product system. Furthermore, the platinum level was disregarded since, in its current form, the aluminium can cannot reach this level, as explained in section 2.2.

The object of the present study was the primary packaging, i.e. the materials which come into direct contact with the product, in this case a 0.33 l aluminium can for the UK market. The C2C certification scheme was only applied to the primary packaging and not the final packed product (i.e. 6-packs of 0.33 l aluminium cans containing beer, packed with hi-cones into a corrugated tray of 4 x 6 cans shrink wrapped as a complete unit). However, in order to estimate the appropriateness of focusing on the can only, a sensitivity analysis

addressed the influence of the secondary and tertiary packaging, as well as of the distribution of the final product (see section 2.3). The content, i.e. the beer, was also excluded from the analysis, since food and beverage are not covered by the scope of the C2C certification program (Cradle to Cradle Products Innovation Institute, 2013).

The function of an aluminium can is to contain a defined volume of beer, typically 25, 33, 44 or 50 cl (Stichling and Nguyen-Ngoc, 2009) depending on the gastronomical/cultural preferences of the final market. The chosen functional unit (FU) was here the containment of 1 hl of beer, in accordance with the Environmental Product Declaration (EPD) of beer (IEC, 2014). For canned beverages the selection of the FU is usually performed on a volume base, alternatively 1000 l (Detzel and Mönckert, 2009) or the volume of 100 cans, which according to the size of the can could be 250 l, 330 l, 440 l, or 500 l (Stichling and Nguyen-Ngoc, 2009).

The system boundaries, presented in Figure 1, included the primary aluminium production, sheet rolling, can body and lid manufacturing, the actual can production which includes lacquering, the filling of the can, and eventually its EoL. For the scenario analysis, exclusions from the system boundaries were the distribution system of the can, use of the can, as well as all the secondary (hi-cones), tertiary (tray, shrink wrap), and quaternary (wooden pallet) packaging manufacturing. The transport of secondary, tertiary and quaternary packaging from the suppliers, as well as the transport of the waste scrap to the EoL, was further excluded. The geographical scope of the study was the UK. We hence applied EoL scenarios relevant for UK, where packaging is collected as part of a mixed collection (ERM, 2008). For the disposal we assumed that all the aluminum cans not recycled were sent to landfill, which is the main disposal option in UK. Thereby it was disregarded that a negligible fraction not being landfilled actually goes to incineration. This chosen approach to model the EoL of the can corresponds well with the fact that the contribution from the EoL of the cans (i.e. both to landfill and incineration) to the overall impact patterns is negligible, amounting to less than 1% (i.e. below the generally accepted cut-off level (Stichling and Nguyen-Ngoc, 2009)).

- Figure 1 around here -

For the part of the cans being recovered we used as a default the EoL recycling approach recommended by the metal industry (Atherton, 2007) to model the closed-loop recycling for aluminium. This approach is indeed the most frequently used approach in the case of aluminium can LCAs, see e.g. (PE Americas, 2010; Stichling and Nguyen-Ngoc, 2009). However, in a further sensitivity analysis, we tested the influence of different EoL modelling approaches on the LCA results by implementing the algorithm recommended by the Product Environmental Footprint (PEF) method (EC, 2013), see section 2.3. Furthermore, we tested the influence of different methodological approaches to credit the avoided environmental impacts related to recycled material, i.e. the traditional crediting method assuming displacement of primary aluminium production and a new crediting method which takes the actual mix of virgin and recycled materials used as a source of raw materials in the market into account (Gala et al., 2015).

Different data sources were used to build the LCI of the aluminium can. The processes of primary aluminium production, sheet rolling, body can and lid manufacturing, and can production (excl. filling) used secondary data based on a study commissioned by Beverage Can Makers Europe (BCME), European Aluminium Association (EAA) and Association of European Producers of Steel for Packaging (APEAL) (Stichling and Nguyen-Ngoc, 2009), which includes state-of-the art data for the can production process. Data on energy consumption during filling are primary data, as included in the InstantLCA PackagingTM tool. The database used to model the LCI were ecoinvent v2.2 for the Gabi and InstantLCA PackagingTM modelling, and ecoinvent v3.1 with Simapro modelling.

We performed the LCIA using different LCIA methodologies, both at midpoint level, i.e. the International Reference Life Cycle Data System (ILCD) recommended method v1.05 (Hauschild et al., 2013), and endpoint level, i.e. ReCiPe 2008 v1.11 relying on the hierarchical perspective and the Europe H/A weighting set (Goedkoop et al., 2009). However, in the beverage packaging sector the use of the proxy LCI indicator non-renewable fossil Cumulative Energy Demand (CED) has been proven to be useful to obtain a preliminary estimation of the environmental impacts of different options (Scipioni et al., 2013). Furthermore, in cases where the environmental impacts are led by fossil fuels consumption, the use of a single LCIA indicator such as the Global Warming Potential (GWP) is considered a good proxy for the other impact categories (Laurent et al., 2010). Therefore we mainly focused our results on the GWP and CED indicators, which are also associated with the highest reliability compared to more uncertain and method dependent impact indicators such as human toxicity (Laurent et al., 2010). The full scope of impact categories at endpoint are considered in a sensitivity analysis (see section 2.3).

2.2 C2C certification requirements

The present study quantified the C2C certification requirements of MR and RE in an LCA of aluminium cans. The MR certification category focuses on the first C2C principle, i.e. the concept of eliminating waste. The MR certification principle quantifies the recycling value of the materials based on a score ranging from 0 to 100 using the so-called “Material Reutilization Score” (MRS). The various C2C certification levels not only require a score for e.g. recycling value, but also improvement strategies to be developed in order to achieve a higher certification level (Cradle to Cradle Products Innovation Institute, 2013).

Two variables are included in the MRS formula, which in the case of material belonging to the technical cycle are: the % of the product considered recyclable (i.e. a material that can be recycled at least once after its initial use phase), and the % of recycled content (RC) in the product. Once the MRS variables are combined, they provide a percentage score (i.e. the MRS) calculated according to equation 1 below (Cradle to Cradle Products Innovation Institute, 2013):

$$MRS = [(\% \text{ of the product considered recyclable}) \cdot 2] + [(\% \text{ RC in the product}) \cdot 1] / 3 \cdot 100 \quad [1]$$

We calculated the MRS for the different C2C certification scenarios, considering the following assumptions: the % of the product considered recyclable is calculated taking into account the composition of the can, made of two aluminium alloys for body and lid, respectively, which are recyclable, and the lacquer, which is not. We used secondary data to calculate the % of lacquer, i.e. 3.2% of the total weight of the finished can (Li and Qiu, 2013). Therefore the percentage of the product considered recyclable is 96.8% and was kept constant across all the scenarios compared in this case study. Under this assumption, the lowest possible MRS, with a 0% RC, is 64.5% while the maximum score with a 100% RC, amounts to 97.9%. We inherently assumed that the two factors in equation (1) are independent from each other, and we included an ideal scenario with 100% RC, even though this cannot currently be achieved due to the 0% recyclability of the lacquer. Equation (1) is valid for all types of materials. In the case of aluminium can assessed here, a platinum grade cannot be achieved due to the lacquer. In the scenarios compared here, we varied the % RC according to the amount of secondary material used in input divided by the total material input (EAA, 2013). RE&CM quantifies the second principle of C2C, i.e. use of current solar income. The end goal is for a product to positively impact the environment with energy usage coming from renewable sources, i.e. photovoltaic, geothermal, wind, hydro and biomass (McDonough and Braungart, 2002). The C2C certification scheme quantifies the amount of energy usage (RE) and emissions for electricity and on-site CO₂ emissions (CM). In this study we focused on the first aspect (RE). The product is graded based on the % usage of energy from renewable sources (% RE). The energy utilization accounts for the aggregated amount of energy needed during the entire life cycle of the can. The two energy inputs, from renewable and non-renewable (NRE) sources, will be adjusted according to energy type utilization demands for the three different levels of C2C certification across the comparative scenarios. The % usage of energy from renewable sources is calculated according to equation 2 [2]:

$$\% RE = (MJ \text{ of } RE) / (MJ \text{ of } RE + MJ \text{ of } NRE) \quad [2]$$

The energy input to the product system is fixed in the InstantLCA PackagingTM tool: for electricity the average electricity mixes defined on a country-specific basis are used, based on 2008 data from the International Energy Agency (IEA). For aluminium production, an aluminium-industry specific mix is used (RDC Environment, 2013). For thermal energy production, the country-specific mix is used (RDC Environment, 2013). Since these parameters are fixed, the RE certification requirement could not be modelled in the scenario analysis with the software InstantLCA PackagingTM tool, and was modelled with Gabi and Simapro. In both softwares the energy processes were modeled based on secondary data (Stichling and Nguyen-Ngoc, 2009), thereby assuming that in can body and lid production, renewable energy was primarily sourced from hydropower and non-renewable was sourced from a combination of natural gas, crude oil and nuclear. For thermal energy, the inputs differ between the can body and the lid. The can body production relies mainly on thermal energy from natural gas (Stichling and Nguyen-Ngoc, 2009) and this was assumed to constitute 100% of the input. The report by Stichling and Nguyen-Ngoc (2009) further states

that the lid production rely mainly on raw oil based energy supply. Therefore, it is assumed that 100% of the non-renewable energy needed for the thermal energy production for the lid is produced by combustion of light fuel oil. For the energy from renewable sources, one of the preferred alternatives to fossil fuels is thermal energy generated from biomass (<http://www.biomassenergycentre.org.uk>), which has been selected as the default source of renewable thermal energy in the UK in this case study. Biomass is considered a sustainable, low carbon emitting thermal energy fuel primarily sourced from wood chips. It can typically be found locally and is particularly abundant within the UK. This is ideal from a C2C perspective as one of the objectives is to use local resources which can be returned to the biological cycle.

In the can filling stage, the only inputs modelled were the energy consumptions, which were modelled assuming hydropower as the primary input for renewable electricity and natural gas as the primary source for non-renewable thermal energy. The first assumption is based on the fact that Carlsberg UK purchases renewable energy credits for electricity (RECS), i.e. certificates guaranteeing that the purchased electricity entering the facility is renewably sourced. The allocated energy is a percentage of the total energy produced by the provider and is bought similar to stocks. To avoid double counting, the amount of renewable energy sold can never exceed the amount produced. For renewable thermal energy production we considered wood energy, which varies proportionally to natural gas depending on the scenario.

We built the LCI adopting a parametric approach, where the key parameters (% RC and % RE) were varied in order to represent the different scenario criteria presented in Table 1. The applied approach has been successfully implemented in the packaging sector, see e.g. in the case of tertiary packaging (Niero et al., 2014a).

Table 1: Summary of the scenarios compared, according to the % recycled content (RC) and % renewable energy (RE) values and indication of the certification level that a product would have with the respective requirements, where B=Bronze, S=Silver, G=Gold.

		% RE			
		0%	5%	50%	100%
% RC	0%	B	S	S	S
	35%	B	S	G*	G*
	50%	B	S	G*	G*
	65%	B	S	G*	G*
	100%	B	S	G*	G*

** These are achieved only if a nutrient management strategy has been developed*

When modelling the scenarios for the LCA we assumed that the system represents a closed-loop, i.e. the collected used beverage cans (UBC) are used to manufacture new beverage cans. From an LCA perspective, we translated this assumption considering that the % RC used in the MRS formula is equal to the percent recycling rate (% RR), defined as recycled aluminium produced from post-consumer scrap as a percentage of aluminium available from post-consumer scrap sources (EAA, 2013), with the remainder going to landfill.

We will discuss the influence of this assumption in a sensitivity analysis, where the PEF formula (EC, 2013) was applied (see section 2.3).

2.3 Sensitivity analyses

Bearing in mind the uncertainties associated with both the LCI and LCIA steps, the validity and robustness of the final outcomes of an LCA should be tested via sensitivity and uncertainty analyses (Guo and Murphy, 2012). In order to do so we performed a set of sensitivity analyses varying the most relevant assumptions:

- S1: choice of the LCA software (InstantLCA PackagingTM tool vs Simapro vs Gabi);
- S2: influence of the EoL modelling approach, i.e. the avoided environmental burdens (Atherton, 2007) vs PEF formula (EC, 2013), and substitution factor (Gala et al., 2015) performed with InstantLCA PackagingTM tool and Simapro;
- S3: influence of exclusion of the secondary, tertiary and quaternary packaging and calculation of their contribution to the overall impact, performed with InstantLCA PackagingTM tool;
- S4: influence of the selection of impact assessment categories, performed with Simapro;
- S5: influence of parameter uncertainty performed applying the Monte Carlo sampling technique using a 1000-run Monte Carlo analysis (Frischknecht et al., 2007), based on the approach presented in Niero et al. (2014b), performed with Simapro.

3. Results

3.1 Scenario analysis

The LCIA GWP 100 results obtained for the scenarios listed in Table 1 are presented in Figure 2, where both the Simapro (IPCC 2013) and Gabi (IPCC 2007) results are reported. The CED results are presented in Figure 3 for Simpro (CED, v1.09).

- *Figure 2 around here* -

- *Figure 3 around here* -

The scenario analysis evaluates in combination the increasing RC/RR along with increasing RE usage, as well as the resulting environmental performance in terms of GWP and CED for each certification scenario. It should be kept in mind that the C2C certification levels presented here only reflect the quantitative requirements, while in complete assessment the certification level is also dependent upon the fulfillment of other qualitative requirements. The results in Figures 2 and 3 illustrate that a higher certification level does not necessarily imply that a product system has lower environmental impact in terms of GWP and CED. Furthermore, a beverage can rated as a silver could yield different environmental performances according to the scenario, e.g. a can utilizing 100% RE and 0% RC/RR (i.e. C2C silver certification) could still perform (much) worse LCA wise than a beverage can with at least 65% RC/RR and 5% RE (i.e. also C2C silver certification).

From the contribution analysis of the case with 50% RC/RR and 0% RE, the most impacting life cycle stages are the can body production and can lid production, where the contribution is driven mainly by primary

aluminium production and to a lesser extent by the thermal energy production. Avoided impacts are attributable to the recycling of the can, assuming that primary aluminium production is avoided 1:1 by the recycled aluminium. Moreover, as shown in Figure 3, even in the scenarios with 100% RE, still a considerable share of the CED is provided by NRE, due to the non-renewable sources used in primary aluminium production.

3.2 Software choice

To test the influence of the software choice (S1) we performed the same calculations with the three different softwares. Not all sets of scenarios could be compared, due to the fixed energy setup in InstantLCA PackagingTM tool, which is based on the UK electricity grid mix (Dones et al., 2007) and non-renewable thermal energy input (hard coal, natural gas and light fuel oil). Therefore, we compared the InstantLCA PackagingTM tool data with the 0% RE and 50% RE scenarios with increasing % RR, with the same scenarios modelled both in Simapro and Gabi. The results of the software comparison are presented in Table 2.

Table 2: Sensitivity analysis on the climate change (CC, kg CO₂ eq) impact at increasing % recycling rate (RR) according to the software (InstantLCA PackagingTM tool, Simapro and Gabi) and their default IPCC factors (i.e. 2007 or 2013) and % RE considered.

	Parameters	% RR						
Software	RE [%]	IPCC	Unit	0%	35%	50%	65%	100%
InstantLCA TM Packaging tool	default ecoinvent v2.2	2007	kg CO _{2eq}	46.6	35.4	30.6	25.8	14.6
Simapro v8.0.4.30	0	2013	kg CO _{2eq}	52.3	41.1	36.3	31.5	20.2
Simapro v8.0.4.30	50	2013	kg CO _{2eq}	47.4	36.2	31.4	26.6	15.3
Gabi 6.4	0	2007	kg CO _{2eq}	65.3	47.8	40.3	32.8	15.2
Gabi 6.4	50	2007	kg CO _{2eq}	60.4	42.9	35.4	27.9	10.4

3.3 EoL modelling approach

To test the influence of the EoL modelling approach and substitution factor on the final outcomes of the LCA study we performed a sensitivity analysis (S2) in both the InstantLCA PackagingTM tool and Simapro, applying the PEF formula, with traditional substitution factor of 1:1 and 0.25:1 as suggested by Gala et al., (2015). We chose the case of 0% RE for comparison, with increasing % RR and assuming 0% RC, 50% RC, and 100% RC (see Table 3).

Table 3: Sensitivity analysis on the climate change (CC, kg CO₂ eq) impact at increasing % recycling rate (RR) according to the software (InstantLCA PackagingTM tool, Simapro) considering the Product Environmental Footprint (PEF) formula with 0% RE and increasing % RC (0, 50, 100) and two sets of substitution factors between primary and secondary aluminum, i.e. 1:1 and 0.25:1.

Parameters			RR				
RC	Software	Unit	0%	35%	50%	65%	100%
0%	InstantLCA TM Packaging tool	kgCO _{2eq}	47.2	42.3	40.2	38.1	33.2
	Simapro v8.0.4.30 – substitution factor 1:1	kgCO _{2eq}	52.4	46.6	44.1	41.6	35.8
	Simapro v8.0.4.30 – substitution factor 0.25:1	kgCO _{2eq}	52.4	51.4	51.1	50.7	49.8
50%	InstantLCA TM Packaging tool	kgCO _{2eq}	39.0	34.1	32.0	29.9	25.0
	Simapro v8.0.4.30 – substitution factor 1:1	kgCO _{2eq}	43.3	37.5	35.0	32.5	26.7
	Simapro v8.0.4.30 – substitution factor 0.25:1	kgCO _{2eq}	43.3	42.4	42.0	41.6	40.7
100%	InstantLCA TM Packaging tool	kgCO _{2eq}	29.9	25.0	22.9	20.8	15.9
	Simapro v8.0.4.30 – substitution factor 1:1	kgCO _{2eq}	34.2	28.4	25.9	23.4	17.6
	Simapro v8.0.4.30 – substitution factor 0.25:1	kgCO _{2eq}	34.2	33.3	32.9	32.5	31.6

3.4 Inclusion of other life cycle stages

C2C certification is applicable to the primary packaging while LCA by definition includes all the life cycle stages of a product, for a food product typically also including the packaging. For packaging this means that secondary and tertiary packaging should also be included in the LCA, as well as the transport from supplier and to customers, see e.g. (Scipioni et al., 2013; Toniolo et al., 2013). Therefore, we used the specific features of the InstantLCA PackagingTM tool, which is customized for Carlsberg packaging, and allows for testing of the influence of one typical configuration of secondary, tertiary and quaternary packaging applied for the 33cl aluminium cans, including default/average transport distances (S3). We considered the default values for transport provided by the InstantLCA PackagingTM tool, i.e. 400 km for secondary, tertiary and quaternary transport, as well as for the transport from the aluminium material factory and the can factory; 29 km from the can supplier to Carlsberg UK facility and finally 100 km for the distribution stage. The extra life cycle stages included in this “inclusion of other life cycles stages test” are those marked as excluded in Figure 1, except for the use stage, which is also neglected in the sensitivity analysis. The results of the inclusion test are shown in Figure 4, which reports the contribution analysis per life cycle stage, displaying the product included in the C2C certification and the contribution from the added life cycle stages, i.e. secondary, tertiary and quaternary packaging production and transport, as well as distribution. The contribution of the omitted life cycle increases from 5% in the case of 0% RR and up to 14% in the case of 100% RR.

- *Figure 4 around here* -

3.5 LCIA methodology: single issue vs endpoint

The LCIA results for the scenarios listed in Table 1 are presented in Figure 5 in the form of aggregated single score calculated in accordance with ReCiPe endpoint modelling, hierarchical perspective, Europe H/A weighting set (Goedkoop et al., 2009) in Simapro (S4). The results in Figure 5 are presented with indication of the impact categories contribution to the overall impact.

- Figure 5 around here -

3.5 Uncertainty analysis

Based on default probability distributions of the input data from ecoinvent v3.1, the Monte Carlo simulation provided the distribution and confidence intervals, i.e. standard deviation divided by the mean of the results of the scenario analyzed for the GWP100 (S5). The results from Monte Carlo simulations, i.e. mean value and confidence intervals, are presented in Figure 6, for a selection of cases, i.e. 0% RE and 100% RE for increasing % RC/RR (0%, 35%, 50% and 100%). Figure 6 also includes the point values obtained in the scenario analysis.

- Figure 6 around here -

4. Discussion

4.1 Validation of the LCA results

The LCIA results on the aluminium can are aligned with the results of other LCA studies on aluminium cans, both in terms of contribution analysis and absolute values for climate change. The results are consistent among the different software used and the differences can be explained by the different datasets and database versions used (mostly for primary aluminium production), as well as different LCIA methods (IPCC 2007 vs IPCC 2013). A detailed investigation of the differences among the different software is however considered beyond the scope of this study.

Furthermore, it should be kept in mind that a direct comparison among the results from different LCA studies is not always straightforward, due to the different system boundary definitions and assumption sets applied. Stichling and Nguyen-Ngoc (2009) performed a comparative LCA for beverage cans including different scenarios with increasing collection rate. They considered a different functional unit, i.e. 1000 cans also with an overall volume of 330 l. When we recalculated these results so that these comply with the functional unit of 1 hl and reflects a specific C2C certification scenario (0% RC and 50% RR), we obtained a value of 33.0 kg CO₂ eq/hl which is coherent with our results. PE Americas (2010) performed a similar study, under American conditions which yielded a comparable value of 39.9 kg CO₂ eq/hl, for a C2C certification scenario with 67.8% RC and 51.6% RR relying on the closed-loop approach and taking into

account the avoided impacts from recycling. (Detzel and Mönckert 2009) obtained a value of 33.5 kg CO₂ eq/hl when modelling German conditions and reflecting a 90% RC of the body of the can and 0% RC of the lid of the can with 75% RR, and 17.5 kg CO₂ eq/hl with a 95% RR, respectively.

Most of the other studies included other impact categories, on top of GWP and CED. As shown in Figure 5, climate change results drive the LCIA single results, and are responsible for almost 50% of the overall score, when both the contribution to human health and ecosystems is taken into account. These results support our choice of presenting and discussing the outcome of the scenario analysis relying on the GWP result set. This has already been proven successful in the case of beverage packaging (Scipioni et al., 2013) and metals (Berger and Finkbeiner, 2010).

LCA results are related with many uncertainties and therefore it is important to present the results not only in terms of absolute single impact category contributions values, but also taking into account the basic uncertainties, which provide an indication of the robustness of the absolute differences of scenarios (i.e. if these are significantly different or not). The results of the Monte Carlo uncertainty analysis in Figure 6 show that despite the possible variability of the outcomes, the environmental impacts expressed as GWP connected with different possible bronze or gold levels are not necessarily significantly different, meaning that in LCA terms it's not always possible to tell the difference between and bronze or gold certification. Whether or not uncertainty is also taken into account when rating the different scenarios according to the C2C certification program remains elusive.

4.2 Recommendations for the Carlsberg Circular Community

The ranking of the 20 scenarios yielded the differences between the GWP impacts associated with different levels of certification, based on variation of two of the parameters, % RC/RR and % RE, which are assumed representative of the MR and RE C2C requirements. When only these two C2C requirements are considered and depending on why that certification level was obtained, it appears that a gold rating does not necessarily entail (significantly) better environmental performance than lower levels. The climate change impacts (Table 2) within the bronze certification level ranges from 52.3 kg CO₂ eq (0% RC, 0% RE) to 20.2 kg CO₂ eq (100% RC, 0% RE), whereas the gold certification level ranges from 36.2 kg CO₂ eq (35% RC and 50% RE) to 10.4 kg CO₂ eq (100% RC, 100% RE) – meaning that there is a considerable GWP overlap among the gold and bronze C2C certification levels.

The influence of recyclability (RC/RR) on the final outcomes is higher than the influence of the RE. The large influence of RC/RR is caused by the burden savings obtained from the avoided primary aluminium production. Since only 5% of the energy used for primary aluminium is required to make secondary aluminium (EAA, 2013), it is evident that RC directly impacts the RE category. When RC increases, the total amount of energy required decreases and hence less energy needs to be converted from a renewable source. The predominant influence of the RC over the RE may be due to the fact that the aluminium can has a high level of recyclability, at least the recyclability in accordance with the MRS formula. The influence of recyclability reveals that there could be an inherent flaw in the way C2C awards its certifications. If

Carlsberg were to prioritize RE over RC, they could possibly achieve gold certification of the can despite the fact that they are impacting the environment significantly more seen from an LCA perspective than if they prioritized RC over RE. Decisions at company level are strongly dependent on economic considerations and this could tempt companies to choose the cheaper solution when different options with different prize tags are available to reach the same certification level even though the cheaper choice could imply larger environmental impacts. The C2C certification program is meant for continuous improvement, and helps identifying the necessary objectives to reach the next certification level for all five categories.

With the creation of the CCC, Carlsberg has taken the first steps towards a C2C future by examining their products from a C2C certification perspective and by driving consumer awareness. An (environmentally) optimized product is only as valuable as the infrastructure will allow. The aluminium can RR in the UK is currently lower than the EU average (Labberton, 2011), there is mostly no dedicated UBC collection and on top of this the different counties have implemented different waste management systems (Farmer et al., 2015). Starting with the Every Can Counts initiative (<http://www.everycancounts.co.uk>), aluminium cans are already being voluntarily separated from other types of UBCs. But in order to build the infrastructure necessary to improve UBC treatment during recycling, Carlsberg UK and the CCC can take the lead in working with the members of its value chain to rethink not only the design of the can but also the way the can is processed during the end of life. Indeed, C2C intends to “*challenge manufacturers to take more responsibility for creating the infrastructure and systems necessary for recovering and recycling materials*”(Cradle to Cradle Products Innovation Institute, 2013). This goes beyond increasing the RRs and involves improved separation during collection. The viability to develop a value network business model for aluminium can in the UK market based on a closed loop supply has been explored by Stewart et al. (2015). The actions outlined (increasing the RR, improve sorting and collection) are aligned with some of the EAA’s recommendations for recycling legislation (EAA, 2014). The last action (application of the correct LCA methodology) will be discussed in the following section.

4.3 Methodological challenges

As concluded by Bjørn and Hauschild, (2013), C2C and LCA are inherently complementary approaches as C2C focuses on an ideal future in terms of absolute sustainability and LCA focuses on the short-term and assesses contemporary systems in relative terms. Bjørn and Hauschild (2013) recommend application of LCA as a “reality check” in order to confirm that the C2C design is applicable in cases where there is a trade-off between energy and material consumption. The C2C certification program was developed as a means to put the C2C vision into practice. Some of the discrepancies between the theory and day-to-day practice of applying C2C in packaging development have been discussed by Toxopeus et al. (2015), including its main focus on product optimization rather than innovation. The five C2C categories are considered to be equal with each carrying equal weight in relation the final certification level. However, the categories can be organized into two levels of C2C certification: product/material on one side and process/company on the other side. MH and MR refer to the product itself; whereas RE&CM, WS and SF

are related with the processes supporting the creation of the product. Based on the results of the present LCA, this category hierarchy could support the idea that RC has a higher priority than RE because it is directly related to the product itself.

The different scopes of C2C and LCA should be kept in mind when assessing the applicability of LCA for C2C certification/validation. A traditional LCA only considers the product life as a snapshot - or rather a snapshot of a product system model covering one life cycle. This conflicts with C2C since C2C considers the “defined use” of the material which is meant to be used in continuous life cycles, not a single snapshot. This is strictly related to the way the continuous use of material should be modelled in LCA. Currently, there is no general agreement on how to conduct the EoL modelling in relation to multiple life cycles and different equally valid approaches can be adopted (Allacker et al., 2014; Thomas and Birat, 2013). However, if we want to use LCA as a tool to support the implementation of the circular economy, we need to be able to overcome the “one life-cycle” approach and move towards a “multiple life-cycle” approach. This shift of perspective challenges the way the benefit from recycling are included in LCA, both in terms of substituted material and its quality compared with the primary material. According to Gala et al. (2015) the traditional 1:1 substitution factor can lead to an overestimation of the environmental credits, since EoL aluminium that is recycled should substitute not only primary aluminium, but the average market mix of both primary and secondary aluminium in use and hence reflecting recycling practices. When introducing a lower substitution factor (0.25:1), our results revealed that the reduction of the potential environmental impacts with increasing % RC is significantly lower compared to the reference case (Table 3). Therefore, the role of % RC in directing the environmental performance improvements of the different C2C scenarios can be questioned. A possibly low “true” potential of increasing RC should be included not only from an LCA perspective, but also in the MRS formula, which currently takes into account only two factors, i.e. the potential recyclability of the material and the % RC, without addressing the primary vs secondary substitution issue. The quantification of the quality factor should be based on the actual aluminium alloy composition, as discussed in Niero and Olsen (2015).

A key aspect in LCA is the life cycle perspective, seeking to include all the relevant life cycle stages necessary to provide the function, i.e. containment of 1 hl of beer, which in the case of packaging are not only the primary packaging (as included in the C2C certification program), but also the secondary, tertiary, quaternary packaging and transport. The sensitivity analysis on the “inclusion of other life cycles stages test” showed that contribution from these materials to the overall impact of the aluminium can product system is marginal, but very much dependent on the level of RR. Therefore the risk to underestimate the potential environmental impacts of the certified product increases at higher certification levels.

A further relevant issue in the C2C design framework is the quantification of the energy requirements. From a C2C perspective, as long as the energy *quality* meets the requirements the *quantity* is irrelevant (Bjørn and Hauschild, 2013). RE&CM are virtually direct trade-offs of energy from renewable and non-renewable sources utilized in the manufacturing process. However, the real world value of these results is dependent on

the actual infrastructure available at the chosen location. If Carlsberg UK were to begin utilizing wood chips in order to replace natural gas for thermal energy production, it is fair to assume that it would not be a seamless transition from fossil to biofuel. Such large production system changes would have to be introduced via gradual replacement over time. As illustrated by the fossil to biofuel transition, C2C and LCA can work well together in forecasting and providing directions on the future impacts of the product and (quantitative) reduction options hereof. C2C provides the strategic milestones (i.e. direction) and LCA provides the potential impacts (i.e. the magnitude of the environmental burden saved) when the milestones are reached. Furthermore, Figure 3 illustrates the total amount of energy required for each scenario on renewably or non-renewably energy supplies. The main issue observed here is that even at 100% RE, there is still NRE being utilized. This is because the existing infrastructure still requires some non-renewable (energy) sources, e.g. in the primary aluminium production, and since the C2C certification levels here included (B, S, G) only considers the manufacturing stage rather than the entire life cycle, C2C misses the fact that NRE is being utilized, by whoever outside the manufacturing stage. The lack of life cycle perspective has already proven to bias the outcomes of the C2C certification for product categories such as office buildings, textiles and TV & lamps categories, with high energy consumption during use stage (Kausch and Klosterhaus, 2015; Llorach-Massana et al., 2015), and is here challenged for aluminium packaging, which has high energy consumption during the raw material manufacturing stage.

4.4 Limitations of our study

The main limitation of this study is the inclusion of only two C2C requirements; three categories (MH, WS, and SF) have indeed been excluded.

MH is an assessment of the material selection and determines which material should be removed from the system due to their health or environmental hazards. From a C2C perspective, the MH level is given based on the amount of A, B, C rated and X- rated materials present in the product. From an LCA perspective, the model formulation is determined based upon the bill of materials. If the two were to be combined, a detailed inclusion of all intended and non-intended uses of the product should be performed, thereby (widely) extending the scope of LCA, which is usually based on operative conditions of a process or defined use of a product. In the practical implementation of the C2C through the C2C certification program, MH emerged to be by far the most important criterion (Toxopeus et al., 2015). Therefore, this aspect should be further investigated, due to the impact of the lacquer on the recyclability of the can. The lacquer issue will be one of the challenges to overcome in order to reach higher certification levels as a new can design strategy would need to be developed in order to replace the current lacquer.

WS is intended to encourage manufacturers to manage their water consumptions, treatment and discharge quality in the best possible way. From a C2C perspective, a grade is given based on the implementation status of optimizing effluent and waste flows from the production site. This involves an assessment of the process chemicals utilized in manufacturing stage. An LCA can utilize this information once all chemicals

are known. The WS criterion can be further investigated through the use of the water footprint framework (ISO, 2014).

SF is slightly more challenging to model as C2C defines it as a purely qualitative measure. It is the exception that proves that C2C and LCA are differing in terms of scope. C2C focuses on product quality and innovation while LCA focuses on improving the environmental sustainability. However, it is recommended to revisit the applicability of social fairness in LCA once social impact assessment in LCA has been further developed.

5. Conclusions

The first objective of the study was to conduct a scenario analysis based on an LCA of the possible C2C certification combinations of MR and RE for a 33cl aluminium can manufactured by Carlsberg in UK. Different scenarios were developed and compared, according to three C2C certification levels (bronze, silver, gold), in terms of % RE and % RC, while the improvements in terms of environmental impact reductions from one certification level to another were quantified, with two main conclusions. First, increasing RC provides more improvements to environmental impacts than increasing RE usage. Secondly, receiving a gold certification is not necessarily preferable seen from an environmental angle than a bronze or silver, since higher certification level does not necessarily mean environmental burden reduction in LCA sense.

Using this information, Carlsberg can visualize the environmental impacts associated with their aluminium beverage cans and identify which actions to prioritize for reaching higher C2C certification levels with largest environmental burden saving in an LCA perspective. The main recommendations for the CCC are hence: to prioritize increasing RC/RR; to explore options to optimize the lacquering process used to make the label, as well as the delacquering process used in the recycling stage; to develop a long term strategy for increasing local renewable energy utilization, as well as a nutrient management strategy before the current certification expires in 2017. Finally, partnership with waste management specialists, e.g. collection and recycling centers, should be established in order to explore improvements in the treatment of the collected UBC and explore ways to improve the recycling rate in the UK.

The second objective of the study was to identify the main challenges and drawbacks in the combined use of LCA and C2C for aluminium packaging in the circular economy framework. From a methodological point of view, we proved that the quantifiable C2C requirements can be modeled in LCA and LCA can provide check and validation points for each certification milestone. The main challenge for LCA is to address the continuous loop of materials and account for the benefits from recycling in a consistent way, with proper quantification of the substitution and downgrading factors. On the other hand, the main challenge for C2C is to guarantee a proper translation of the C2C principles into the C2C certification program avoiding burden shifting and to find a balance between the different certification criteria, e.g. through the implementation of a set of weighting criteria. Given their complementarity, both approaches should be combined in the decision making needed for closing product loops within the circular economy framework.

Acknowledgments

The authors would like to thank Carlsberg Foundation for funding the postdoc project “Design of Cradle to Cradle® - Inspired System for Beer Beverage Packaging”, as well as Eskild Andersen and Håkon Langen from Carlsberg Group for their support during data collection. The study reported in this paper is based on the oral contribution presented at the Society and Material International Conference (SAM 9) in Luxembourg, 11-12 May 2015.

References

- Allacker, K., Mathieux, F., Manfredi, S., Pelletier, N., De Camillis, C., Ardenne, F., Pant, R., 2014. Allocation solutions for secondary material production and end of life recovery: Proposals for product policy initiatives. *Resour. Conserv. Recycl.* 88, 1–12. doi:10.1016/j.resconrec.2014.03.016
- Atherton, J., 2007. Life Cycle Management Declaration by the Metals Industry on Recycling Principles. *Int. J. Life Cycle Assess.* 12, 59–60. doi:http://dx.doi.org/10.1065/lca2006.11.283
- Berger, M., Finkbeiner, M., 2010. Correlation analysis of life cycle impact assessment indicators measuring resource use. *Int. J. Life Cycle Assess.* 16, 74–81. doi:10.1007/s11367-010-0237-7
- Bjørn, A., Hauschild, M.Z., 2013. Absolute versus Relative Environmental Sustainability. *J. Ind. Ecol.* 17, 321–332. doi:10.1111/j.1530-9290.2012.00520.x
- Bor, A.-M., Hansen, K., Alan Riviere, A., Alvarado, C., van den Wittenboer, W., 2011. Usability of Life Cycle assessment for Cradle to Cradle purposes. NL Agency, Utrecht.
- Braungart, M., McDonough, W., Bollinger, A., 2007. Cradle-to-cradle design: creating healthy emissions – a strategy for eco-effective product and system design. *J. Clean. Prod.* 15, 1337–1348. doi:10.1016/j.jclepro.2006.08.003
- Carlsberg Group, 2015. Carlsberg Group CSR Report 2014.
- Cradle to Cradle Products Innovation Institute, 2013. Cradle to Cradle CertifiedCM. Product standard Version 3.0.
- de Pauw, I.C., Karana, E., Kandachar, P., Poppelaars, F., 2014. Comparing Biomimicry and Cradle to Cradle with Ecodesign: a case study of student design projects. *J. Clean. Prod.* 78, 174–183. doi:10.1016/j.jclepro.2014.04.077
- Detzel, A., Mönckert, J., 2009. Environmental evaluation of aluminium cans for beverages in the German context. *Int. J. Life Cycle Assess.* 14, 70–79. doi:10.1007/s11367-008-0057-1
- Dones, R., Bauer, C., Bolliger, R., Burger, B., Heck, T., Röder, A., Institut, P.S., Emmenegger, M.F., Frischknecht, R., Jungbluth, N., Tuchscheid, M., 2007. Life Cycle Inventories of Energy Systems : Results for Current Systems in Switzerland and other UCTE Countries. Villigen and Uster.
- EC, 2013. Commission Recommendation of 9 April 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations.
- EMF, 2013. Towards the circular economy. Opportunities for the consumer goods sector.
- ERM, 2008. Review of Packaging Deposits System for the UK. Final Report.
- EAA, 2013. Environmental Profile Report for the European Aluminium Industry April 2013- Data for the year 2010 Life Cycle Inventory data for aluminium production and transformation processes in Europe.
- EAA, 2014. EAA Position Paper on the EU Waste legislation.
- Farmer, T.D., Shaw, P.J., Williams, I.D., 2015. Destined for indecision? A critical analysis of waste management practices in England from 1996 to 2013. *Waste Manag.* doi:10.1016/j.wasman.2015.02.023
- Frischknecht, R., Jungbluth, N., Althaus, H.-J., Doka, G., Heck, T., Hellweg, S., Hirschler, R., Nemecek, T., Rebitzer, G., Spielmann, M., Wernet, G., 2007. Overview and Methodology. Ecoinvent Report No. 1. Swiss Centre for Life Cycle Inventories. Dübendorf, Switzerland.
- Gala, A.B., Raugei, M., Fullana-i-Palmer, P., 2015. Introducing a new method for calculating the environmental credits of end-of-life material recovery in attributional LCA. *Int. J. Life Cycle Assess.* 20, 645–654. doi:10.1007/s11367-015-0861-3
- Gatti, J.B., Queiroz, G.D.C., Elena, E., Garcia, C., 2008. Reducing Environmental Impacts: Aluminium

- Recycling Recycling of Aluminum Can in Terms of Life Cycle Inventory (LCI). *Int. J. Life Cycle Assess.* 13, 219–225.
- Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., Toulmin, C., 2010. Food security: the challenge of feeding 9 billion people. *Science* 327, 812–8. doi:10.1126/science.1185383
- Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J., R, van Z., 2009. ReCiPe 2008, A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level.
- Guo, M., Murphy, R.J., 2012. LCA data quality: sensitivity and uncertainty analysis. *Sci. Total Environ.* 435-436, 230–43. doi:10.1016/j.scitotenv.2012.07.006
- Hauschild, M.Z., Goedkoop, M., Guinée, J., Heijungs, R., Huijbregts, M., Jolliet, O., Margni, M., Schryver, A., Humbert, S., Laurent, A., Sala, S., Pant, R., 2013. Identifying best existing practice for characterization modeling in life cycle impact assessment. *Int. J. Life Cycle Assess.* 18, 683–697. doi:10.1007/s11367-012-0489-5
- IEC, 2014. Environmental Product Declaration (EPD) certified. Carlsberg Beer.
- ISO, 2006a. Environmental management. Life cycle assessment. Principle and framework. ISO 14040:2006. Geneva, Switzerland.
- ISO, 2006b. Environmental management. Life cycle assessment. Requirements and guidelines. ISO 14044:2006. Geneva, Switzerland.
- ISO, 2014. ISO 14046 Environmental management -- Water footprint -- Principles, requirements and guidelines.
- Kausch, M.F., Klosterhaus, S., 2015. Response to “Are Cradle to Cradle certified products environmentally preferable? Analysis from an LCA approach.” *J. Clean. Prod.* doi:http://dx.doi.org/10.1016/j.jclepro.2015.11.008
- Klingmair, M., Sala, S., Brandão, M., 2013. Assessing resource depletion in LCA: a review of methods and methodological issues. *Int. J. Life Cycle Assess.* 19, 580–592. doi:10.1007/s11367-013-0650-9
- Labberton, M.G., 2011. Progress on Aluminium Packaging Recycling in Europe – focus on beverage cans : deposit systems versus other collection schemes.
- Laurent, A., Olsen, S.I., Hauschild, M.Z., 2010. Carbon footprint as environmental performance indicator for the manufacturing industry. *CIRP Ann. - Manuf. Technol.* 59, 37–40. doi:10.1016/j.cirp.2010.03.008
- Li, N., Qiu, K., 2013. Study on delacquered beverage cans by vacuum pyrolysis for recycle. *Environ. Sci. Technol.* 47, 11734–8. doi:10.1021/es4022552
- Llorach-Massana, P., Farreny, R., Oliver-Solà, J., 2015. Are Cradle to Cradle certified products environmentally preferable? Analysis from an LCA approach. *J. Clean. Prod.* 93, 243–250. doi:10.1016/j.jclepro.2015.01.032
- McDonough, W., Braungart, M., 2002. *Cradle to cradle*. North Point Press. New York.
- Negrelli, A.J., 2015. An Environmental Assessment of Reducing Carlsberg’s Use of Virgin Aluminium. Technical University of Denmark.
- Niero, M., Di Felice, F., Ren, J., Manzardo, A., Scipioni, A., 2014a. How can a life cycle inventory parametric model streamline life cycle assessment in the wooden pallet sector? *Int. J. Life Cycle Assess.* 19, 901–918. doi:10.1007/s11367-014-0705-6
- Niero, M., Olsen, S.I., 2015. Circular economy : to be or not to be in a closed product loop ? A Life Cycle Assessment of aluminium cans with inclusion of alloying elements. *Submitt. to Resour. Conserv. Recycl.*

- Niero, M., Pizzol, M., Bruun, H.G., Thomsen, M., 2014b. Comparative life cycle assessment of wastewater treatment in Denmark including sensitivity and uncertainty analysis. *J. Clean. Prod.* 68, 25–35. doi:10.1016/j.jclepro.2013.12.051
- PE Americas, 2010. Life Cycle Impact Assessment of Aluminum Beverage Cans. Final Report.
- RDC Environment, 2013. Instant LCA Packaging™ Tool. Methodological Report.
- Scipioni, A., Niero, M., Mazzi, A., Manzardo, A., Piubello, S., 2013. Significance of the use of non-renewable fossil CED as proxy indicator for screening LCA in the beverage packaging sector. *Int. J. Life Cycle Assess.* 18, 673–682. doi:10.1007/s11367-012-0484-x
- Sevigné-Itoiz, E., Gasol, C.M., Rieradevall, J., Gabarrell, X., 2014. Environmental consequences of recycling aluminum old scrap in a global market. *Resour. Conserv. Recycl.* 89, 94–103. doi:10.1016/j.resconrec.2014.05.002
- Speck, R., Selke, S., Auras, R., Fitzsimmons, J., 2015a. Choice of Life Cycle Impact Assessment software can impact packaging system decisions. *Packag. Technol. Sci.* 28, 579–588. doi:10.1002/pts
- Speck, R., Selke, S., Auras, R., Fitzsimmons, J., 2015b. Life Cycle Assessment Software: Selection Can Impact Results. *J. Ind. Ecol.* n/a–n/a. doi:10.1111/jiec.12245
- Stewart, R., Niero, M., Murdock, K., Olsen, S.I., 2015. A framework for green value network business models : the case of a closed loop supply for aluminum beverage cans. Submitt. to *Int. J. Prod. Econ.*
- Stichling, J., Nguyen-Ngoc, D., 2009. Life Cycle Inventory and Impact Analysis for Beverage Cans. Final Report. PE International.
- Thomas, J.-S., Birat, J.-P., 2013. Methodologies to measure the sustainability of materials – focus on recycling aspects. *Rev. Métallurgie* 110, 3–16. doi:10.1051/metal/2013054
- Toniolo, S., Mazzi, A., Niero, M., Zuliani, F., Scipioni, A., 2013. Comparative LCA to evaluate how much recycling is environmentally favourable for food packaging. *Resour. Conserv. Recycl.* 77, 61–68. doi:10.1016/j.resconrec.2013.06.003
- Toxopeus, M.E., de Koeijer, B.L. a., Meij, a. G.G.H., 2015. Cradle to Cradle: Effective Vision vs. Efficient Practice? *Procedia CIRP* 29, 384–389. doi:10.1016/j.procir.2015.02.068
- Trucost, 2014. Impacts of the cradle to cradle certified products program. Technical report.
- Verghese, K.L., Horne, R., Carre, A., 2010. PIQET: the design and development of an online “streamlined” LCA tool for sustainable packaging design decision support. *Int. J. Life Cycle Assess.* 15, 608–620. doi:10.1007/s11367-010-0193-2

Figure captions:

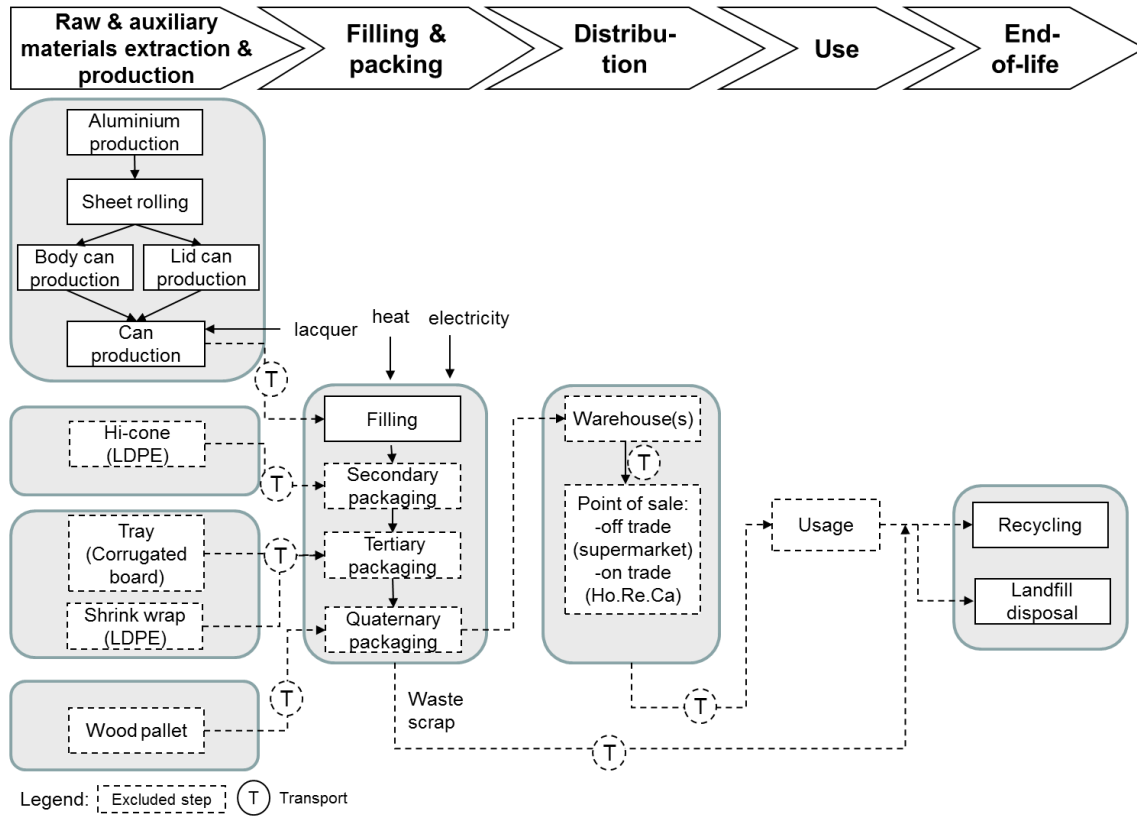


Figure 1. System boundaries with inclusion of main input and output. Excluded steps are marked with dashed line.

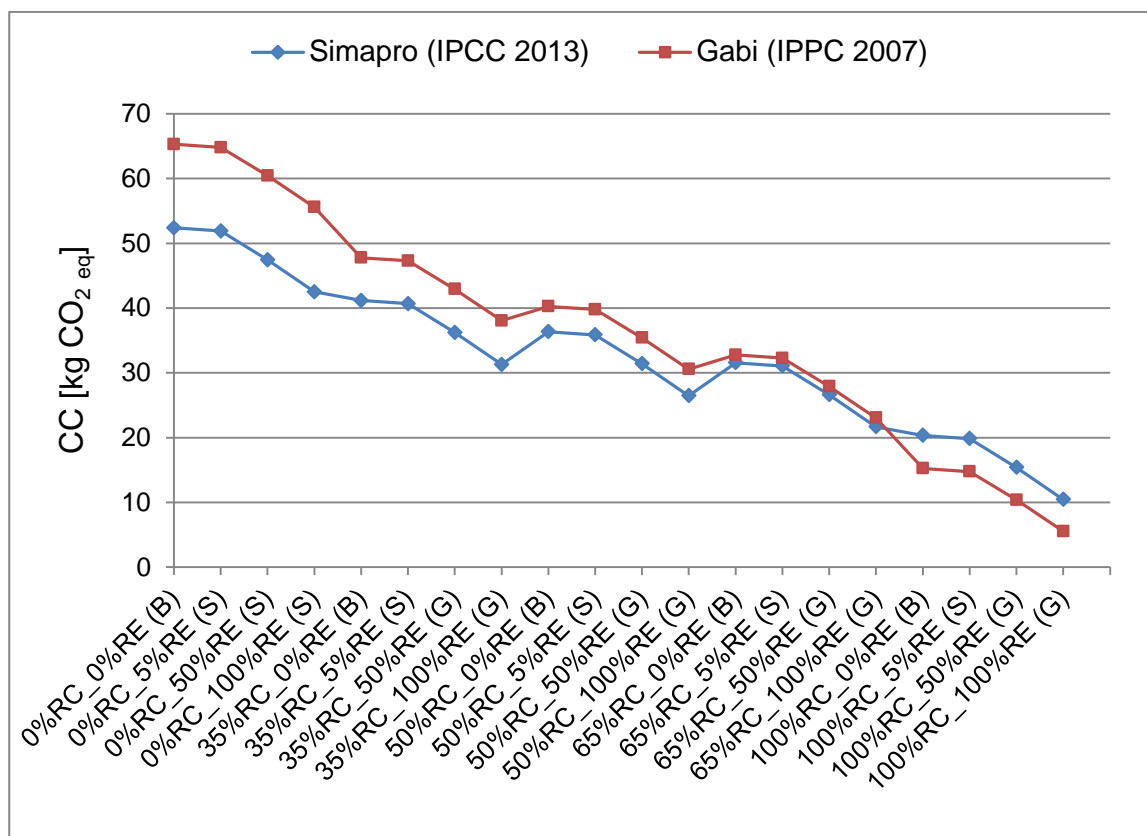


Figure 2. C2C certification scenarios for climate change (CC), according to the combination of % RC and % RE and final score (in brackets, where B=Bronze, S=Silver, G=Gold).

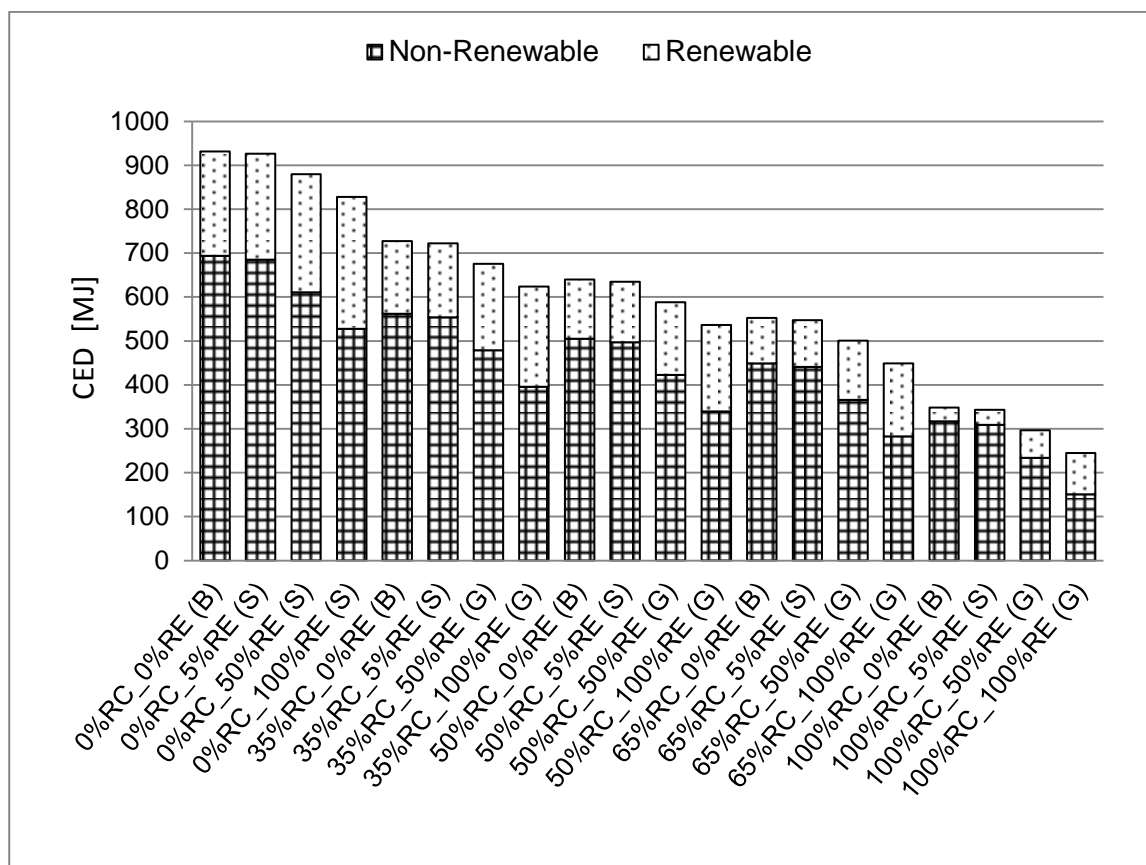


Figure 3. C2C certification scenarios for Cumulative Energy Demand (CED), according to the combination of % RC and % RE and final score (in brackets, where B=Bronze, S=Silver, G=Gold).

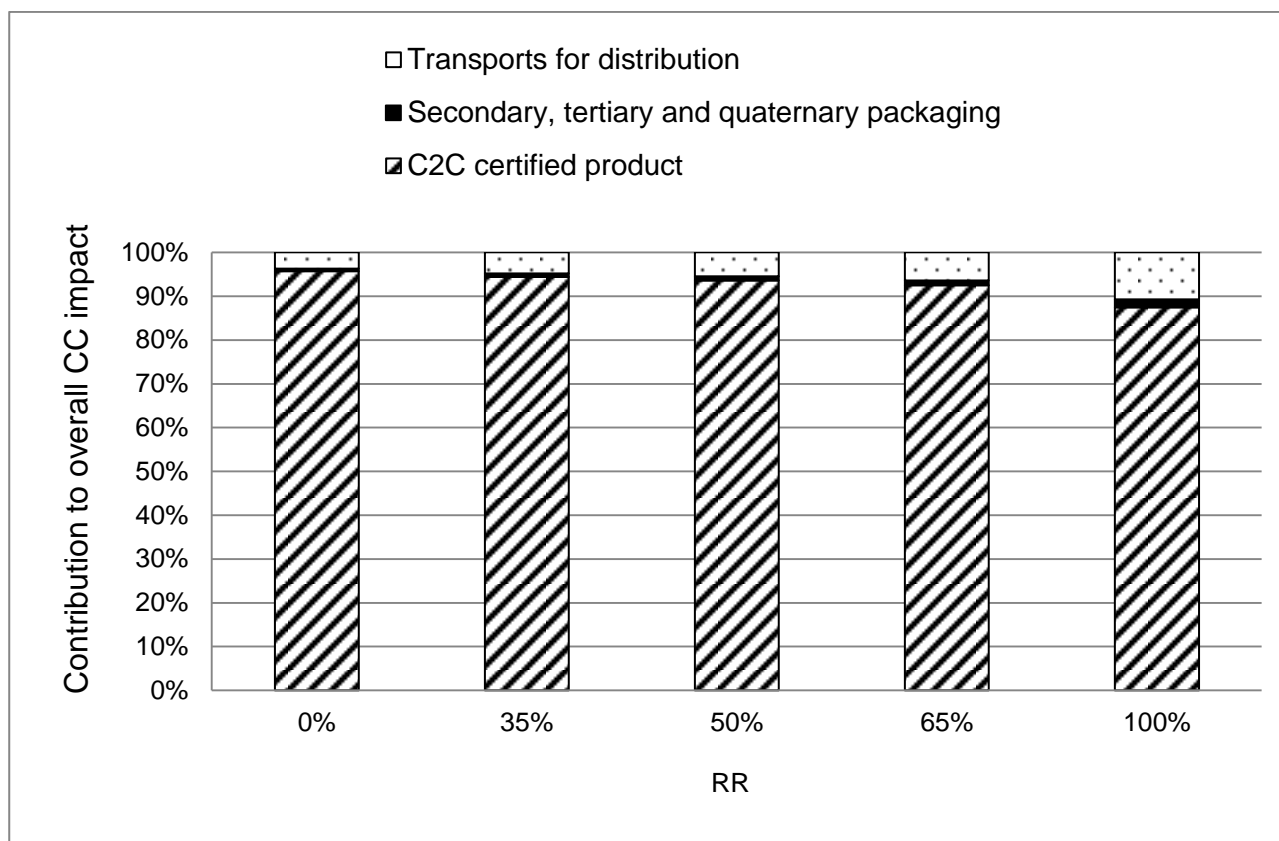


Figure 4. Contribution analysis for climate change of the aluminium can considering all the life cycle stages, performed with InstantLCA PackagingTM tool.

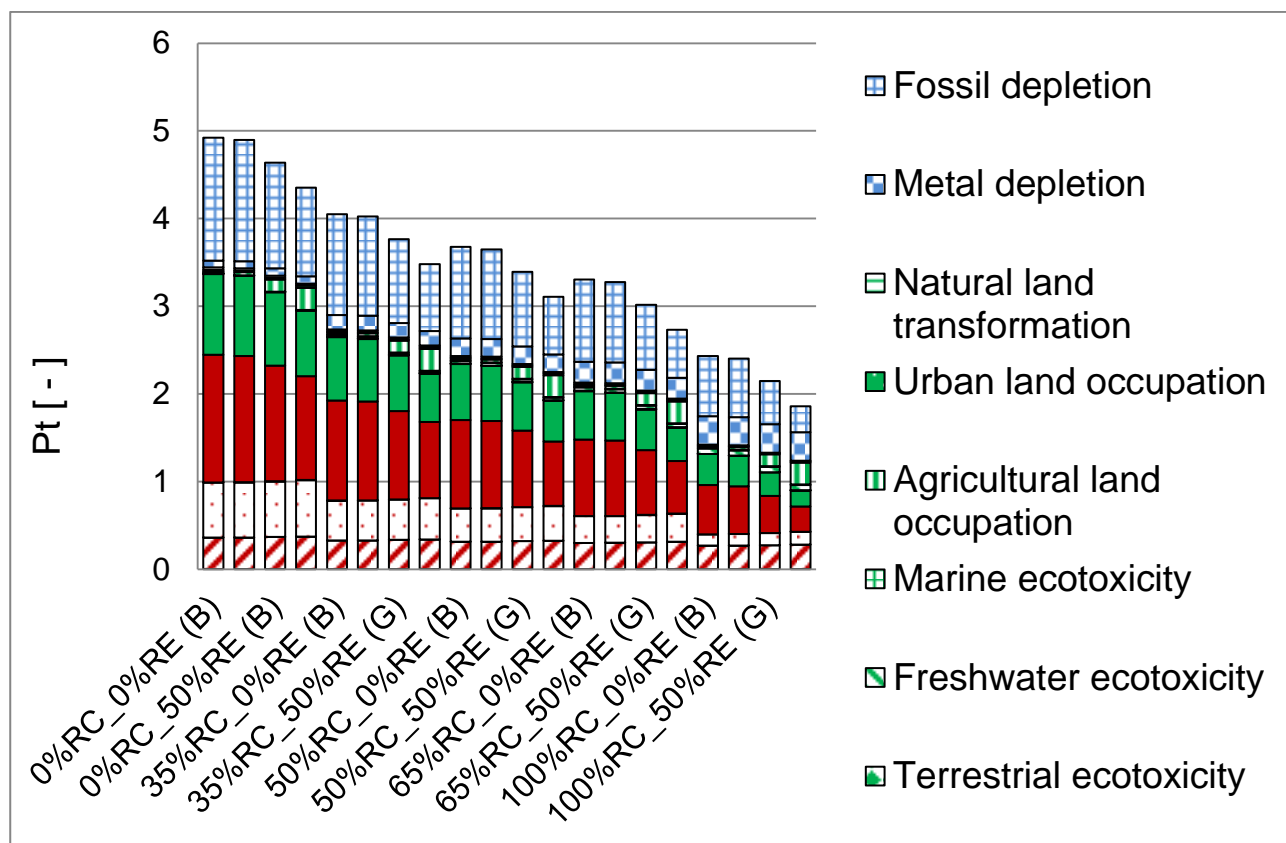


Figure 5. C2C certification scenarios at endpoint level single score considering the ReCiPe Europe H/A, according to the combination of % RC and % RE and final score (in brackets, where B=Bronze, S=Silver, G=Gold).

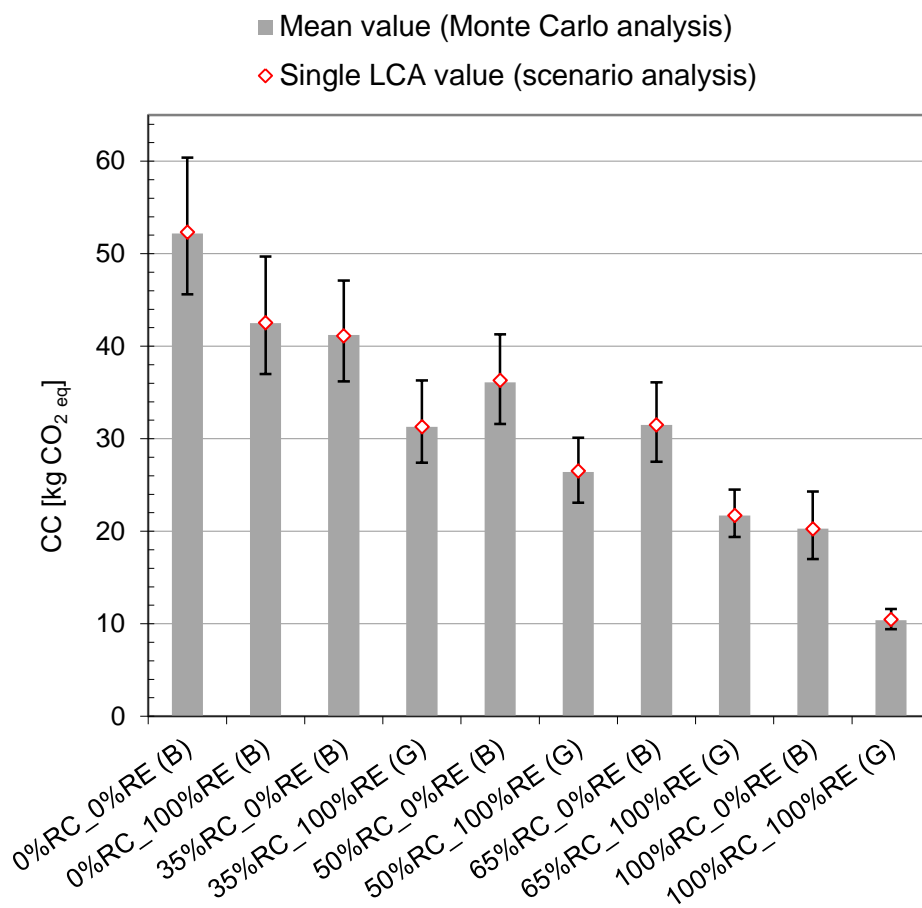


Figure 6. Climate change results obtained with GWP100 IPCC 2013 with 95% confidence interval (error bars) calculated through Monte Carlo simulation for a selection of scenarios listed in Table 1. The error bars indicate that in 95% of the cases the LCIA would fall within the range.